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5 Reconciling land / ocean moisture transport variability  
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7 in reanalyses with P-ET in observationally-driven  
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9 land surface models  
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14 Franklin R. Robertson<sup>1</sup>, Michael G. Bosilovich<sup>2</sup> and Jason B. Roberts<sup>1</sup>  
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17 <sup>1</sup>NASA / Marshall Space Flight Center, Earth Science Office  
18 MSFC, AL 35812  
19

20 <sup>2</sup>GSFC Global Modeling and Assimilation Office  
21 Greenbelt, MD 20771  
22  
23

24  
25 Corresponding author: Franklin R. Robertson  
26 ([pete.robertson@nasa.gov](mailto:pete.robertson@nasa.gov))  
27 tel: (256) 961-7836  
28  
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## Abstract

Vertically-integrated atmospheric moisture transport from ocean to land, VMFC, is a dynamic component of the global climate system but remains problematic in atmospheric reanalyses with current estimates having significant multi-decadal global trends differing even in sign. Regional VMFC trends over continents are especially uncertain. Continual evolution of the global observing system, particularly step-wise improvements in satellite observations, has introduced discrete changes in the ability of data assimilation to correct systematic model biases, manifesting as non-physical variability. Land Surface Models (LSMs) forced with observed precipitation, P, and near-surface meteorology and radiation provide estimates of evapotranspiration, ET. Since variability of atmospheric moisture storage is small on interannual and longer time scales,  $VMFC = P - ET$  is a good approximation and LSMs can provide an alternative estimate. However, heterogeneous density of rain gauge coverage, especially the sparse coverage over tropical continents, remains a serious concern.

Rotated Principal Component Analysis (RPCA) with pre-filtering of VMFC to isolate the artificial variability is used to investigate artifacts in five reanalysis systems. This procedure, though ad hoc, enables useful VMFC corrections over global land. P-ET estimates from seven different LSMs are evaluated and subsequently used to confirm the efficacy of the RPCA-based adjustments. Global VMFC trends over the period 1979-2012 ranging from  $0.07$  to  $-0.03 \text{ mm d}^{-1} \text{ decade}^{-1}$  are reduced by the adjustments to  $0.016 \text{ mm d}^{-1} \text{ decade}^{-1}$ , much closer to the LSM P-ET estimate ( $0.007 \text{ mm d}^{-1} \text{ decade}^{-1}$ ). Neither is significant at the 90 percent level. ENSO-related modulation of VMFC and P-ET remains the largest global interannual signal with mean LSM and adjusted reanalysis time series correlating at 0.86.

## 1. Introduction

Moisture transport to land from the global oceans is a crucial process linking the global water and energy cycles and is also at the heart of societal concerns regarding terrestrial water availability, food security, exposure to extreme weather events, and climate change. Recent best estimates of the net atmospheric transport of water to land (Rodell et al. 2014) put the climatological amount at  $45.8 \pm 6.7 \times 10^3 \text{ km}^3 \text{ yr}^{-1}$ , or about 40% of precipitation falling over land. The remainder of land precipitation arises from moisture recycling via evapotranspiration, ET (Eltahir and Bras, 1994; Trenberth 1999; Bosilovich and Schubert, 2002). The *variability* of this transport and its potential long-term trend at regional scales are emerging as a prime concern. Tropical circulations linked to sea-surface temperature (SST) variability exert first order controls on the delivery of water to land by virtue of El Niño / Southern Oscillation (ENSO) events (Ropeleski and Halpert, 1987; Dai and Wigley, 2000; Gu et al, 2007; Robertson et al, 2014). Mid-latitude storm track changes embodying teleconnections with tropical forcing also have significant variations at higher latitudes. Over longer time scales Pacific Decadal Variability (PDO / PDV), (e.g. Power et al, 1999; Dai 2013; Lyon et al, 2013) and other basin scale phenomena (e.g. the Atlantic Multi-decadal Oscillation, AMO, Enfield et al, 2001; Sutton and Hodgson, 2005; Ting et al, 2011) also modulate moisture transport. Anthropogenic radiative forcing changes and the consequent hydrologic cycle effects are expected to produce regional variations, encapsulated in the “wet get wetter / dry get drier” paradigm (Chou and Neelin, 2004) wherein hydrologic extremes are expected to increase. As yet, evidence for this behavior in observational data sets is weak at best (Greve et al, 2014). There is also substantial uncertainty as to trends in soil moisture dryness depending on diagnostic approaches and choice of observed precipitation and surface meteorological forcing (Dai, 2011; Sheffield et al, 2012, Trenberth et al, 2014). Untangling the

role of these varied water and energy cycle mechanisms and their relationship to moisture transport continues to be a challenging task.

Moisture transport syntheses are routinely produced by reanalysis efforts (e.g. Kalnay et al, 1996; Onogi et al, 2007; Saha et al, 2010; Dee et al, 2011; Rienecker et al, 2011; Kobayashi et al, 2015) that blend diverse measurements of wind, moisture and temperature and other observations with first guess estimates from model short-term forecasts. While reanalyses effectively reconcile observations with physically-based dynamical models, there are a number of practical problems which result in moisture transport fields typically having substantial systematic time-dependent biases (Trenberth et al, 2011; Robertson et al, 2011; Lorenz and Kunstmann, 2012; Trenberth and Fasullo, 2013; Robertson et al, 2014). The root of the difficulty lies in the fact that model physics (e.g. moist convective parameterizations, turbulence and radiation) each have shortcomings so that assimilating models have biased climatologies. Once initialized, model forecasts (first guesses for analyses) “drift” toward a preferred state that differs from reality. But input data streams that correct this drift are non-stationary in the sense that observing system data densities, and satellite observations especially, have a *time dependent* ability to correct the model first guess fields. Therefore discrete biases develop in water and energy fluxes and transports.

For reanalyses the vertically-integrated atmospheric moisture budget over land grid points is,

$$\frac{\partial W_a}{\partial t} = \text{VMFC} - P + \text{ET} + \text{ANA} , \quad (1)$$

i.e.,  $W_a$ , vapor plus condensate increases as the result of vertically-integrated atmospheric moisture flux convergence (VMFC), evapotranspiration, ET, and is depleted by precipitation, P. In reanalyses, the analysis increment (ANA) represents the departure of the forecast from the analysis



divided by the temporal length of the corrector step; specifically in the case of MERRA and MERRA-2, the forcing needed to drive the evolving reanalysis to the final analysis in a 6h corrector step. Ideally this term should be randomly distributed about zero. Instead, time-dependent biases typically characterize ANA, reflecting bias contained in each of the physical terms in (1). Many previous studies (Trenberth and Guillemot, 1998; Lorenz and Kunstmann, 2012; Trenberth and Fasullo, 2013) suggest that VMFC estimates have more consistency among reanalyses than P-E derived from the model physics. But still, significant global land trends in VMFC were found by these studies.

These issues are seen in Figure 1a which shows reanalysis VMFC monthly anomalies around their respective annual mean. Trends over the period 1979 to 2012 range between -0.03 to 0.08 mm d<sup>-1</sup> decade<sup>-1</sup> (Table 1) and represent roughly -2.0% to 5.0% of the climatological annual means. These trends are difficult to justify physically given recent estimates of P and ET changes (New et al, 2001; Jung et al, 2010) over recent decades. Discontinuities in the satellite record, in particular with the beginning of Special Sensor Microwave Imager (SSM/I) series in July 1987, the Advanced Microwave Sounding Unit-A (AMSU A) in late 1998, and Atmospheric Interferometer Sounder (AIRS) in 2002 are known to link with abrupt changes in water and energy fluxes (Bosilovich et al, 2011; Trenberth et al, 2011 and Robertson et al, 2011; 2014; Bosilovich et al, 2015).

LSMs and other related diagnostic models constrained by observations of precipitation, near-surface atmospheric variables and radiation offer an independent estimate of terrestrial P-ET. In these observationally-constrained models, the water budget has the form

$$\frac{\partial W_T}{\partial t} = P - ET - RO \quad (2)$$

129

130 where column terrestrial water ( $W_T$ , soil plus vegetation) is sustained by P but depleted by runoff,  
131 RO, and ET. Through efforts at the same institutions involved in global data assimilation (e.g.  
132 NASA, NCEP and ECMWF) and various internationally coordinated programs (e.g. the Global  
133 Land Data Assimilation System, [Rodell et al, 2004]; the Global Soil Wetness Project, GSWP and  
134 its successors, GSWP-2 and 3 [Dirmeyer et al, 1999, 2006]; Water and Global Change, WATCH,  
135 [Harding et al, 2011]; Trends and Drivers of Regional Sources and Sinks of Carbon Dioxide,  
136 TRENDY, [Sitch et al, 2013]), reasonably mature diagnoses of P-ET are now available. These  
137 syntheses of land surface state and fluxes have facilitated the quantitative study of droughts and  
138 hydrologic variability-- their scale, intensity, and some assessment of changes on a continental and  
139 global basis (e.g. Koster et al, 2009, 2011; Wisser et al, 2010; Haddeland et al, 2011; Sheffield et  
140 al, 2012; van Dijk et al, 2013). Figure 1b shows corresponding P-ET monthly anomalies from a  
141 number of these sources, along with their ensemble mean. To the extent that atmospheric moisture  
142 storage anomalies on monthly time scales are small reanalysis VMFC and P-ET should be  
143 equivalent. At interannual to near-decadal time scales the agreement between these two quantities  
144 is reasonably good with systematic deficits of (excess) moisture transport to land and smaller  
145 (larger) P-ET during El Niño (La Niña) events. El Niño events in 1982/1983, 1986/1987,  
146 1991/1992, 1997/1998 coincide with anomalously weak ocean to land moisture transport. After  
147 the turn of the century only the 2004/2005 and 2009/2010 events are prominent. At longer scales  
148 though the large trends in many of the reanalyses ( $0.08$  and  $0.07$   $\text{mmd}^{-1}$   $\text{decade}^{-1}$  for MERRA and  
149 CFSR) are not shared by the LSMs whose mean trend is  $0.007$   $\text{mmd}^{-1}$   $\text{decade}^{-1}$ . Against the  
150 prominent interannual and longer excursions the mean LSM global land trend is not significant at  
151 the 0.90 level.

152 Further evidence for the likelihood of small trends in these budget components comes from the  
153 time series of annual global runoff shown in Figure 2, (Dai, 2009; updated by Dai, 2016). The  
154 values shown here are now in terms of  $\text{mmy}^{-1}$  since the RO values are aggregated over water years  
155 (OCT through SEP). The RO trend ( $0.26 \text{ mmy}^{-1}$ ) is roughly one half that of P-ET, so that (2)  
156 implies a net continental water storage trend over the 30 plus year period. This estimate is likely  
157 quite uncertain, although recent work by Reager et al. (2016) finds storage rates of  $0.71 (+/- .20)$   
158  $\text{mmy}^{-1}$  over the period 2002-2014 from GRACE measurements. The relevant point here though is  
159 that the independent RO and P-ET estimates both provide evidence that large multi-decadal trends  
160 in reanalysis VMFC are exaggerated. Taken together with the known inconsistencies introduced by  
161 the changing observing system and other observational evidence against such large global trends,  
162 the VMFC decadal trends should be treated with considerable skepticism.

163 The objective of this paper is to explore reanalysis VMFC discrepancies with independent  
164 LSM-based estimates in more detail. Specifically: (1) We aim to characterize and quantify  
165 observing system influences that produce non-physical trends in reanalysis VMFC trend over  
166 global land. We explore some of the regional patterns of variability, noting how sensitive global  
167 VMFC is to regional uncertainties. (2) In this process, we consider the P-ET record of several  
168 observationally-constrained LSMs as a surrogate for validation of VMFC. But uncertainties in  
169 forcing data as well as the model formulations are still important error sources (Jimenez et al, 2011  
170 and Mueller et al, 2013). Thus, we examine differences among the P-ET estimates and evaluate  
171 their utility as a means of reanalysis validation. (3) We then show that using Rotated Empirical  
172 Orthogonal Function (REOF) analysis, along with some pre-filtering, artificial steps and trends  
173 induced by changing satellite data streams can be largely isolated and removed.

174

## 175    **2. Data**

176        Our investigation depends primarily on monthly mean data from global reanalyses and  
177    observationally constrained land surface models. Since available fields are at different native or  
178    archived grid resolutions, we interpolated all data to a 1.0 degree latitude by longitude resolution.  
179    Unless otherwise noted, all variability estimates are anomalies that were calculated by removing  
180    from the total fields a monthly resolved climatology for the respective data sets at each gridpoint  
181    over the period Jan 1979 through Dec 2010. Some minor departures from these dates are noted in  
182    the discussion below.

### 183    *a. Reanalyses*

184        VMFC is calculated from five state-of-the-art reanalysis projects— the NASA Modern-Era  
185    Retrospective analysis for Research and Applications, MERRA, (Rienecker et al. 2011) and an  
186    updated version MERRA-2 (Gelaro et al. 2016; Molod et al, 2015; Takacs et al, 2015); the  
187    European Centre for Medium Range Weather Forecasting (ECMWF) Interim Reanalysis, ERA-I,  
188    (Dee et al. 2011); the new 55-year reanalysis produced by the Japanese Meteorological Agency,  
189    JRA-55, (Kobayashi et al, 2015) that extends from 1958 to 2012; and the National Centers for  
190    Environmental Prediction Climate Forecast System Reanalysis, NCEP / CFSR (Saha et al. 2010).  
191    For ERA-I and JRA55 northward and eastward components of vertically-integrated moisture  
192    transport were available and the horizontal flux divergences of these quantities were computed.  
193    For MERRA and MERRA-2 the divergence of the vertically-integrated transport was archived as a  
194    standard product. CFSR VMFC has been derived by Trenberth et al. (2011) and was obtained  
195    directly from the National Center for Atmospheric Research.

In addition to the references noted here more in-depth documentation of these reanalysis products, assimilating models and data used can be found at <https://reanalyses.org/>. Some of the more salient details of these reanalyses are provided in Table 2.

*b. Land Surface Models*

Products generated by LSMs rely on forcing data from reanalysis output as a first guess but, crucially, incorporate in situ observations, gauge precipitation and some satellite data to relax substantially the biases of these initial estimates (e.g. Dirmeyer et al, 1999; Sheffield et al, 2006; Weedon et al, 2011). Still, there remain uncertainties whose origin and characteristics can be complex; thus, evaluation and validation of ET (and sensible heating and soil moisture) estimates is an ongoing process with assessments that have targeted model formulation and input forcing (Kato et al, 2006; Badgley et al, 2015) and used river discharge, GRACE, and field data (Zaitchik et al, 2010; Rodell et al, 2011) for validation. Intercomparison and validation efforts within larger collaborative efforts of LandFlux (Jimenez et al, 2011; Mueller et al, 2013) and WaterMIP (Haddeland, 2011; Harding et al, 2011) are generating needed quantitative perspectives on flux and surface state uncertainties.

Seven different estimates of P-ET are used in this study, each constrained by observational forcing: three are from land surface hydrology models: the Global Land Data Assimilation System initiative, GLDAS-2 (Rodell, 2004); MERRA-Land (Reichle et al, 2011; 2012); the MERRA-2 land component (Reichle and Liu, 2014) that runs as part of the assimilation but uses an observation corrected precipitation analysis; and ERA-Interim Land (Balsamo et al, 2015). Two of the models ORCHIDEE (Organising Carbon and Hydrology In Dynamic Ecosystems) model (Kriner et al, 2005) and the Common Land Model, CLM4C, (Oleson et al, 2010; Lawrence et al, 2011) are dynamic global vegetation models used in the Trends and Drivers of Regional Sources

219 and Sinks of Carbon Dioxide (TRENDY) initiative (Sitch et al, 2013), a contribution to the  
220 REgional Carbon Cycle Assessment and Processes (RECCAP; Canadell et al., 2013). Finally, a  
221 diagnostic ET estimate from the MPI-BGC flux data set (Jung et al., 2009; 2010) uses a machine-  
222 learning methodology to scale-up eddy covariance measurements from FLUXNET (Baldocchi et  
223 al. 2001). A surface energy balance constraint is combined with absorbed photosynthetically  
224 active radiation data derived from SeaWiFS (Gobron et al. 2006). For consistency with the  
225 derivation of this ET data set we combine it with GPCC V6 precipitation to construct P-ET  
226 gridded values. Details and further references for these products are given in Table 3.

### 227 *c. Other Data*

228 From the CMIP-5 AMIP archive ([http://cmip-pcmdi.llnl.gov/cmip5/data\\_portal.html](http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html)) we  
229 selected five data sets for analysis that roughly sample the breadth of model diversity: the GFDL-  
230 HIRAM-C180, GISS-E2-R, HadGEM2-A, MIROC5, and MRI-CGCM. Their monthly P-ET  
231 fields are available for the period January 1979 through December 2008. Global runoff as  
232 presented by Dai, 2009 (updated by Dai, 2016) were used in Figure 2. These data are used for  
233 comparison of time series behavior.

234

### 235 **3. Isolating non-physical changes in reanalysis VMFC**

236 In the process of generating reanalyses, the analysis increment, ANA, in (1) yields information  
237 on the mismatch between the first guess (model forecast) and the observations. Schubert and  
238 Chang (1996) employed a least squares analysis of the projection of the physical terms in the  
239 moisture budget onto ANA to infer errors in the GEOS reanalysis budget terms. Robertson et al.  
240 (2014) used the results of a principal components analysis (PCA) applied to MERRA ANA to  
241 regress out artifacts in the water and heat budget flux terms. That study showed that non-physical

242 modes of variability, due largely to increasing amounts of satellite data and their ability to counter  
243 model biases, can have prominent regional to global structure. Since ANA is not readily available  
244 for all of the reanalyses used in this study we use PCA in conjunction with pre-filtering to identify  
245 these non-physical components in the reanalysis VMFC.

246 The form of the continental moisture budget equation we analyze is

247

$$248 \quad \text{VMFC} = P - ET + \text{Res}, \quad (3)$$

249

250 where each term is a monthly gridpoint anomaly. Here we have subsumed all uncertainties  
251 regarding the moisture storage term and the remaining imbalance into a residual term. This  
252 framework differs from (1) since we are taking P-ET from the LSMs, a source independent of the  
253 reanalyses. How effectively can we then dissect reanalysis VMFC into its physical part and that  
254 due to observing system effects?

255 Simple PCA provides a compact treatment of variance contributions by mutually orthogonal  
256 modes in terms of the spatial coherence of the variability (EOFs) and associated temporal  
257 variability (PCs). Successive modes explain the maximum amount of remaining variance.  
258 However, individual PCA modes cannot generally be equated with specific sources of variability.  
259 Nor can we guarantee physical signals and assimilation artifacts to be collected into separate  
260 modes. After examining raw VMFC EOFs and PCs from a PCA decomposition for each  
261 reanalysis it was noted that while apparent non-physical variability dominated the leading few  
262 modes, these were typically mixed with additional ENSO signals.

To identify the artifacts more clearly we first pre-filtered the VMFC. The first eight PCs of an EOF analysis of Global precipitation Climatology Center (GPCC) precipitation were used to largely remove VMFC physical signals at each grid point via principal component regression:

$$VMFC^{pf} = VMFC - \sum_{i=1}^m cov(VMFC, PC_i) \cdot PC_i, \quad (4)$$

where  $VMFC^{pf}$  is the pre-filtered VMFC and  $PC_i$  is the  $i$ th PC of the GPCC precipitation. To the extent that ET co-varies with P, we can think of this step as removing VMFC co-varying with P and ET. This approach has two attributes: First, it does not add any source of physical variability to VMFC since by construction it only removes VMFC signals that project onto P variability. This would not be the case if we just subtracted the P anomalies from those of VMFC. Second, since we are first removing much of the physical VMFC signal, this minimizes the likelihood that any subsequent analysis of  $VMFC^{pf}$  will mistakenly identify physical low-frequency behavior or trends as being artifacts.

We then take a conservative approach of using just the leading few modes of a rotated PCA of  $VMFC^{pf}$  as representing the bulk of the artifact signals. We chose to rotate the modes (i.e. make linear combinations of them) to collect regional variability into fewer leading modes. Using the Varimax constraint (Richmond, 1986), we rotated the leading 10 modes. The raw PCs were scaled by  $-1/\sqrt{\text{eigenvalues}}$  before input to the rotation matrix so as to preserve orthogonality among the rotated PCs yet relax that constraint for the rotated EOF patterns. The product of the RPC time series and the REOFs recovers each mode's contribution to VMFC variability. The resulting "artifact" modes can then be subtracted from the *raw* VMFC leaving  $VMFC^*$ , the estimated physical variability,



$$VMFC^* = VMFC - \sum_{j=1}^n REOF_j^{pf} \cdot RPC_j^{pf} , \quad (5)$$

where  $REOF_j^{pf}$  and  $RPC_j^{pf}$  are the  $j$ th REOF and RPC of  $VMFC^{pf}$ . Inserting (5) into (3) we have

$$VMFC = VMFC^* + \sum_{j=1}^n REOF_j^{pf} \cdot RPC_j^{pf} = P - ET + Res . \quad (6)$$

Since  $VMFC^{pf}$  is determined by an ad hoc procedure that only minimizes the presence of true physical variability we can't regard this whole signal as being the artifact to be removed. Thus, a more conservative approach is to use only the leading modes that have some obvious relationship to changes in the assimilated data streams. To the extent that  $VMFC^*$  and P-ET agree, the Res term is explained by the sum of the “artifact” modes and other non-systematic VMFC and P-ET errors. Results of this analysis and the methods to determine the number of modes used along with a sensitivity analysis are presented in section 7.

#### 4. Regional VMFC and P-ET contributions to global land averages

##### *a. Regional Interannual Signals and Trends*

To determine the extent to which variability shown in Figure 1a, b is manifest regionally, we first examine maps of root mean square (RMS) monthly mean VMFC anomalies (Figure 3, left panel) and trends (right panel) for each reanalysis over the period 1979-2012. Anomalies are departures from the respective monthly varying climatologies. For comparison, the RMS and trend of the ensemble LSM P-ET and reanalysis VMFC are shown in Figure 4. The anomalies were composited before the RMS and trend were calculated. In addition the MERRA and

309 MERRA-2 values were averaged to form one sample so as maintain diversity of the reanalysis  
310 systems and LSMs considered.

311 In general terms, the RMS values of ERA-I, JRA-55 and MERRA (Figure 3) agree reasonably  
312 with those of the LSM ensemble mean (Figure 4). MERRA-2 and CFSR RMS values are a factor  
313 of 2 or more greater in many places over tropical continents. One striking feature is that except for  
314 MERRA all reanalyses have larger RMSs over west central Africa compared to that of the LSM  
315 ensemble mean. LSM values are typically less than  $1.0 \text{ mm d}^{-1}$  there whereas reanalysis values  
316 exceed  $1.5$  to  $2.0 \text{ mm d}^{-1}$  over broad areas and are frequently much larger. There are great  
317 observational challenges over tropical continents, especially Africa, not only for the radiosonde  
318 density but also for rain gauge and surface atmospheric measurements. Over much of South  
319 America, reanalysis VMFC variability agrees well with that of the LSMs, again with MERRA-2  
320 and CFSR being much larger. Variability over the headwaters of the Amazon Basin is slightly  
321 stronger in the LSM versus the reanalysis ensembles. A separate center of strong variability  
322 common to the reanalyses and LSMs (Figure 4a, b) is present over the La Plata Basin, a region of  
323 strong convective activity and storm track origination, both modulated by ENSO.

324 Reanalysis VMFC trends show regional structure that does not average out in the ensemble  
325 mean and contrasts in many areas with ensemble LSM trends (Figure 3 right, Figure 4c, d). Strong  
326 downward trends exceeding  $1 \text{ mm d}^{-1} \text{ decade}^{-1}$  dominate Central Africa in all reanalyses except for  
327 CFSR which is strongly positive. These signals are much weaker in the LSMs. Upward trends  
328 exceeding  $1 \text{ mm d}^{-1} \text{ decade}^{-1}$  in the reanalyses are seen in East Africa but are not found in the LSMs.  
329 The Maritime Continent and upper reaches of the Amazon basin trend upward in all reanalyses in  
330 agreement with the LSMs. Negative VMFC tendencies extend from southern Brazil through the  
331 La Plata Basin but are much less organized than the negative P-ET values from the LSMs.

Somewhat surprising is the lack of agreement between the reanalyses in terms of trends over the U.S. In this area of dense observational data LSM trends are near zero but ERA-I and JRA-55 have strong downward trends. In another data rich region over northern and eastern Europe, the upward VMFC trends extend across all reanalyses but are very weak in the LSMs.

One might wonder whether variability of moisture storage Eq. (1) might be large enough to explain some of the discrepancies between LSMs and the reanalyses. We calculated monthly mean  $\partial W_a / \partial t$  from MERRA-2 using 1-hour data since this intra-monthly time resolution provides the largest amplitude signal. Monthly mean, atmospheric storage anomalies averaged over global land (not shown) are an order of magnitude less than VMFC and P-ET values shown in Figure 1a, b. However, regional monthly mean RMS  $W_a$  tendencies can reach near 0.50 mm/day in subtropical regions and are not negligible for constructing moisture budgets over many areas. Nevertheless, these RMS tendencies are much smaller over tropical continents and cannot explain the reanalysis / LSM discrepancy over Central Africa. Furthermore, regional trends in moisture storage are negligible and cannot explain the differing trends for VMFC compared to P-ET in Figures 3 and 4.

## 5. Analysis of regional VMFC errors

The results of section 4 reinforce our assertion that the differences between the LSM P-ET and the reanalyses VMFC variability on longer than interannual time scale are attributable to systematic reanalysis errors that have largest expression over tropical regions. We now examine several of these specific regions where the LSM P-ET and reanalysis VMFC differ so strongly.

### *a. Western Equatorial Africa*

354 Based on the trend differences in Figures. 3 and 4 we examine the region extending from 10°  
355 W to 20°E and from 5°S to 5°N. Time series of VMFC for the reanalyses and mean LSM P-ET is  
356 shown in Figure 5a. Each reanalysis shows a distinct change in behavior near the end of 1988.  
357 ERA-I drops sharply in a step-like manner as does JRA55. MERRA amplitudes decrease by half  
358 but with far less evidence of a change in mean value. Attributing these changes to a specific data  
359 stream is difficult. SSMI ingest began in late 1987 for the reanalyses but these effects have to be  
360 indirect since the radiances are not used over land. The transition between NOAA9 and NOAA11  
361 MSU data also occurs in late 1988. Near the end of 1998 MERRA and JRA55 show a return to a  
362 higher amplitude seasonal oscillation with opposite polarity of the pre-1988 period. The MERRA  
363 VMFC anomalies also begin a drop over the next 5-7 years. CFSR shows a pronounced increase  
364 in 2002 consistent with the beginning of AIRS data. Characteristic of each data set is a change in  
365 the annual cycle at the end of 1988 and again in 1998. The annual cycle phase shifts between  
366 these periods and its amplitudes decrease in the 1988-1998 period. Clearly, these signals are not  
367 physical.

368 Some insight into MERRA's behavior can be gleaned from Figure 5b. In addition to the  
369 MERRA VMFC anomalies here we also plot the first two PCs of the global, vertically-integrated  
370 moisture analysis increment, ANA, which is the forcing needed to drive the forecast as close as  
371 possible to the analysis of observations. These PCs are analogous to those plotted in Figure 7 of  
372 Robertson et al. (2011). PC1 minus PC2 also almost exactly recaptures the VMFC time series.  
373 The systematic, non-random behavior of the two PCs is evidence of systematic changes in the  
374 ability of the data to correct the model forecast first guess. PC1 shows a small but clearly visible  
375 drop in late 1987 coincident with SSMI availability. Further distinct drops in late 1998 and again  
376 in late 2000 correspond to NOAA15 and NOAA16 AMSU-A data onset. PC2 carries the main

377 signal of the seasonal cycle change. The distinct reduction in seasonal cycle amplitude between  
378 1992 and late 1998 corresponds to the tenure of NOAA12. This PC2 behavior is common to all  
379 three reanalyses except CFSR suggesting that some combination of satellite-induced changes in  
380 the moisture analysis are significant and that the temporal stability of the reanalysis moisture  
381 budgets in this region is unreliable.

382 *b. Coastal Ecuador / Colombia*

383 The coastal Ecuador / Colombia region we examined is land area encompassed within the  
384 boundaries of Eq. to 10N and 80W to 70W. The choice of this area is motivated by examination of  
385 the PCA results to be discussed in section 7 (not shown). Clearly ERA-I is the outlier here (Figure  
386 5c), particularly with respect to the jump in VMFC in the spring of 2004. This zero-order change  
387 appears associated with the assimilation of METAR surface pressure reports beginning at this time  
388 (Figure 11 in Dee et al, 2011). It is unclear as to exactly why these data produce this effect but  
389 assimilation of surface pressures that are in disagreement with the first guess forecast could cause  
390 analyzed mass changes that subsequently affect the divergent wind, vertical motion and,  
391 ultimately, moisture transport fields. These effects can then propagate some distance before being  
392 damped. Despite the small area of influence this large near zero-order change in VMFC is the  
393 primary signal of ERA-I RPC2. In this region we also see some evidence of jump-like behavior for  
394 ERA-I VMFC anomalies in late 1987 although the presence of what appear to be ENSO-related  
395 signals in 1982/83 and 1986 complicate the actual magnitude of changes. Why this VMFC  
396 increase is more pronounced for ERA-I than in MERRA or JRA55 is not yet clear. Except for this  
397 ERA-I problem after NH Spring 2004, the agreement between the LSM mean and the reanalyses is  
398 quite good after about 1990.

399

400 *c. Central U.S.*

401 A large downward trend in ensemble mean VMFC over the central U.S. was noted in Figures.  
402 3 and 4c, driven primarily by ERA-I and JRA-55. The time series in Figure 5d shows a distinct  
403 downward transition for these two reanalyses of approximately  $0.6 \text{ mm d}^{-1}$  at the end of 1994.  
404 Since VMFC climatological values are of comparable size in this region (Figure 6a) this represents  
405 a significant change in the moisture balance. Although there is also a decrease in P-ET from the  
406 LSMs before and after 1995, that change is much more gradual. A change in sources of  
407 conventional data from historical archives to the ECMWF operational feed beginning in 1995  
408 (Uppala et al, 2005) may explain its distinct VMFC decrease In ERA-I. JRA-55 incorporated this  
409 same data as used by ECMWF (Kobayashi et al, 2015) which may explain the similar  
410 discontinuity in that system. Complicating this interpretation is the fact that 1995 also marks the  
411 transition from NOAA 11 to NOAA 14 sounder coverage. Because of the diurnal drift of the PM  
412 satellite equatorial crossing times there was approximately a 3h diurnal cycle difference between  
413 these two sensors. Bosilovich et al. (2015) have analyzed VMFC behavior in MERRA but note  
414 that this shift occurs near 2000 and may be more related to the assimilation of ATOVS and AIRS  
415 data. The exact attribution of the VMFC changes to different data steams remains to be settled; yet,  
416 it is clear that even over data rich regions such at the continental U.S. significant VMFC artifacts  
417 exist.

418

## 419 **6. LSM P-ET signals and uncertainties**

420 Although observationally-constrained LSMs offer a physically consistent estimate of terrestrial  
421 water balance, there exist uncertainties stemming not only from model physics formulation but  
422 from the quality of the forcing data (Badgley et al, 2015). Precipitation data sets (e.g. GPCC,

423 Global Precipitation Climatology Project [GPCP] and others) differ in sampling, gauge under-  
424 catch, and data quality. More problematic is near-surface meteorology and radiative forcing.  
425 These variables are taken from reanalyses too but are bias adjusted using surface observations and  
426 satellite radiative fluxes (e.g. Sheffield et al, 2006, Weedon et al, 2011). Given the contrasts noted  
427 between reanalysis VMFC and LSM P-ET it is necessary to assess uncertainties in the LSMs to  
428 further quantify their credibility vis-à-vis the reanalyses.

429 Recent work by the LandFlux-EVAL community has highlighted uncertainties in LSMs,  
430 diagnostic retrievals and reanalyses. In an initial assessment of flux estimates over the 1993-1995  
431 period, Jimenez et al. (2011) find ET uncertainties of order  $0.50$  to  $0.70 \text{ mm d}^{-1}$  relative to an  
432 annual mean of about  $1.60 \text{ mm d}^{-1}$ . Mueller et al. (2013) extend this study in developing a baseline  
433 time series of flux estimates including interannual variability and trends. They attribute much of  
434 this uncertainty to differences in precipitation forcing used, the influence of water limited ET  
435 regimes and interception by vegetation. On the other hand, there also exists a fair degree of  
436 sensitivity to model formulation evident when LSMs are run using identical forcing data  
437 (Schlosser and Gao, 2009). Lipton et al. (2015) point to ET differences between satellite driven  
438 diagnostic approaches and LSMs noting sensitivities to surface parameters and LSM forcing  
439 precipitation. Still, Mueller et al. (2013) find realistic interannual variations in ET from composites  
440 of these methods are present, including an upward trend between 1989 and 1997 followed by  
441 downward ET trend of during the 1998-2005 period. This behavior is most robust for the LSMs  
442 and echoes the earlier results of Jung et al. (2010). One common finding from these and other  
443 studies is that no single model can be regarded as sufficient and that multiple models with  
444 alternative forcing offer the most reliable syntheses of fluxes.

445 LSM ensemble mean climatological mean P-ET patterns (Figure 6a) look very much like  
 446 precipitation climatologies with large values over the Amazon Basin, Maritime Continent, and S.E.  
 447 Asia. Storm tracks impinging on the west coasts of N. America and Chile are present. Still,  
 448 quantitative differences exist among mean P and ET climatological means (not shown). Despite  
 449 the climatological uncertainties, the global anomalies in Figure 1b show good coherence. To  
 450 assess more deeply the character of the P-ET anomalies comprising the ensemble estimate we  
 451 examine two statistical metrics. The mean signal-to-noise ratio (S/N) is defined as  $S/N$   
 452  $\equiv \sigma_{LSM}^2 / \overline{\sigma_{LSM}^2}$  where  $\sigma_{LSM}^2$  is the square of the ensemble mean monthly P-ET anomaly and  
 453  $\overline{\sigma_{LSM}^2}$  is the mean of the individual squared departures of the P-ET anomalies from the ensemble  
 454 mean monthly anomaly. The S/N diagnostic (Figure 6b) is a local measure of uncertainty among  
 455 the LSM members in defining P-ET monthly anomalies. Densely populated and gauged areas of  
 456 the eastern US, Europe and China have systematically high values ranging from 5 to 8. The  
 457 periphery of Australia and South America also show values in the range of 3 to 5. Deserts (the  
 458 Sahara, Central Asia, and the interior of Australia) have the lowest values owing to sporadic rain  
 459 as well as a dearth of gauges. S/N values within key tropical precipitation regimes of Brazil, New  
 460 Guinea and central Africa are typically 3 or less and likely suffer most directly from insufficient  
 461 gauge density. These values are for 1.0 degree resolution data and it is important to keep in mind  
 462 that spatial averaging to coarser resolution of several degrees enhances these numbers  
 463 significantly.

464 For a more global skill metric we use the anomaly correlation coefficient (ACC) first  
 465 introduced by Miyakoda et al. (1972):

$$466 \quad ACC \equiv \frac{\langle p_{ij} m_{ij} \rangle}{\left( \langle p_{ij}^2 \rangle \langle m_{ij}^2 \rangle \right)^{1/2}} \quad (7)$$



Here,  $p_{i,j}$  are the P-ET anomalies at gridpoint  $i, j$  at any given time for any data set and the ensemble mean anomaly is defined by  $m$ . The angle brackets denote area-weighted averaging over all gridpoints  $i, j$  within the  $60^\circ$  N/S land domain. ACC values measure spatial pattern fidelity as a function of time. Because we lack independent P-ET validation on these scales these diagnostics are more a measure of P-ET sensitivity to input data and model formulation than of accuracy. Results for the seven different LSM P-ET data sets relative to the six-member ensemble mean are given in Figure 6c. (As noted earlier we average the MERRA-Land and MERRA-2 P-ET values as input to the LSM ensemble mean.) MPI-BGC and ORCHIDEE both use GPCC precipitation. ERA-I uses GPCP precipitation which is strongly tied to GPCC gauge data but also differs because of an adjustment to deal with under-catch of gauges. Thus these three precipitation forcing data sets dominate the six member ensemble mean. Values are reasonably stable and generally lie in the range of 0.75 to .95. Experience has shown that values above 0.60 generally are indicative of agreement on the synoptic scale. Thus, from a global coherence perspective, the data sets are similar in their spatial patterns. Sensitivity to the precipitation forcing has a significant influence. Accordingly, MPI-BGC and ORCHIDEE ACC values are each strongly correlated with the ensemble mean; ERA-I Land also shows high correlations. CLM4C ACC values tend to decline in time, especially after 2000. The much smaller number of precipitation gauges used in the CRU TS3.10 product forcing for CLM4C has been shown to lead to a systematic overestimation of precipitation since the mid 1990s (Trenberth et al, 2014; Dai and Zhao, 2016). This appears to influence the lowering CLM4C correlations with time. MERRA-Land and MERRA-2 P-ET values are systematically low although this happens in part because the Climate Prediction Center "Unified" (CPCU) and CPC Merged Analysis of Precipitation (CMAP) precipitation data represent one sample compared to effectively three GPCC forcing sets. There are notable departures though

with MERRA-Land before 1982 and GLDAS-2 Noah in 2006. These periods reflect outliers that originate in the precipitation forcing (CPCU, and the amalgam of data sets that are used for Noah).

ACC calculations performed separately for P and ET (not shown) yielded uniformly high correlations for the former ( $>0.80$ ) while those for ET averaged between 0.5 and 0.8. The lower ET correlations likely reflect the varied physical formulations among the models and the uncertainties in radiative forcing and near-surface moisture and temperature.

## 7. Isolating artifacts via REOF analysis (Assessing space / time variability)

To the extent that we believe the mean LSM P-ET trends (Figure 4b) the differences with the VMFC trends in Figures 3 (right hand side) and 4c indicate the regional trend errors or artifacts inherent in the raw reanalyses. In this section we now determine how effectively the RPCA methodology can be used to capture these effects in a few modes.

### *a. Adjustment effects on regional trends*

In section 3 we outlined the methodology of applying RPCA to the quantity  $VMFC^{pf}$  in order to identify the leading structures and temporal variability of artificial variability induced by changes in observing system input. For most of the reanalyses a single RPCA mode,  $n=1$ , identified the globally-averaged trends characterized as step-like transitions. However, it was found that typically three modes were needed to effectively capture regional trend artifacts. This determination was made by visually inspecting the RPCs and EOFs of each reanalysis  $VMFC^{pf}$  and confirming that those modes contained RPC “discontinuities or steps” that coincided with satellite changes such as SSMI, AMSU or AIRS. We also confirmed that these modes made changes that reduced the regional discrepancy between the trend patterns of VMFC in Figure 3 and the ensemble LSM P-ET in Figure 4d. Only the MERRA and MERRA-2 reanalyses showed that

513 additional modes were significant in changing regional trends. Thus, we applied  $n=5$  for MERRA  
514 and MERRA-2 and  $n=3$  for the others as constituting the signal of changes induced by evolving  
515 assimilation data input. The sensitivity of trend patterns to inherent subjectivity of this selection  
516 process is discussed below.

517 This new VMFC estimate for each reanalysis,  $VMFC^*$ , can then be compared to P-ET of the  
518 ensemble mean LSMs. Though  $VMFC^*$  is now not formally independent of P-ET, none of the P  
519 variability has modified  $VMFC^*$ . The effects of these potential adjustments are presented in  
520 Figure 7. The left panel contains the area-averaged VMFC signal (black) and diagnosed area-  
521 average of the artifact that must be removed (red line). The right panel contains the trends in  
522  $VMFC^*$ , the adjusted reanalyses after this artifact signal has been removed. At the bottom of  
523 Figure 7 is the ensemble mean trend of  $VMFC^*$ . Note the geometric progression of the color scale.  
524 (Recall that we have averaged the MERRA and MERRA-2 data and considered it as one of four  
525 reanalysis systems.)

526 It is clear from Figure 7 (left panel, red lines) that  $VMFC^{pf}$  collects a large amount of trend or  
527 low frequency variability. For example, the impact of AIRS after 2002 in elevating CFSR VMFC  
528 is quite apparent. SSMI availability after 1987 changes ERA-I and JRA-55 noticeably. The large  
529 ERA-I VMFC jump in 2004 over coastal Ecuador / Colombia (Figure 4c) has a significant global  
530 impact. The artifact time series for each reanalysis also has high frequency signals since  
531 significant observing system changes such as SSMI, AMSU and AIRS also affect the VMFC  
532 annual cycle. After adjusting the reanalyses at each gridpoint the spatial trend patterns (Figure 7,  
533 right panel) and the ensemble mean (bottom) are much smaller compared to those in Figure 3 and  
534 show significant changes in structure. Over central Africa the amplitudes of  $VMFC^*$  and LSM P-  
535 ET decreases are much more consistent. Both ensemble  $VMFC^*$  and LSM P-ET (Figure 4d)

536 trends hint at a tendency for increases in moisture convergence to the south over Zambia / Angola  
 537 and north over portions of the Sahel. This pattern suggests perhaps increasing annual latitudinal  
 538 excursion of the ITCZ in these regions. MERRA and CFSR VMFC\* no longer have huge upward  
 539 trends over Australia and the large VMFC increases over East Africa common to all reanalyses  
 540 have been removed. The Amazon basin shows increased moisture convergence over time with  
 541 associated reductions over southern Brazil. There remain differences though with the LSMs  
 542 positioning the P-ET increases over the headwaters region and the reanalyses having the upward  
 543 VMFC\* trends more toward the east. An interesting aspect of this analysis is the relatively small  
 544 fraction of VMFC<sup>pf</sup> total variance needed to explained these regional trend artifacts: JRA55  
 545 (18.09%), ERA-I (14.15%), MERRA (19.08%), MERRA-2 (15.29%) and CFSR (11.61%). This  
 546 indicates that the bulk of VMFC<sup>pf</sup> variability does not project onto regional VMFC<sup>pf</sup> trends. Each  
 547 reanalysis' leading mode largely explains the global average land trend and contributes typically  
 548 about 6%. Since the pre-filtering removes much of the physical signal we interpret this remaining  
 549 VMFC<sup>pf</sup> as predominantly error in higher frequency VMFC regional signals.

550 The global land area-averaged VMFC\* trends (60° N/S) shown in Figure 8 are now each much  
 551 reduced. The ensemble mean value (Figure 8b) is now 0.016 (+/- 0.13) mmd<sup>-1</sup>decade<sup>-1</sup> over the  
 552 period 1979 to 2012. This result is much closer to the mean trend of the LSMs (0.007 [+/-0.010]  
 553 mmd<sup>-1</sup>decade<sup>-1</sup>) and the AMIPs (0.012 [+/- 0.016] mmd<sup>-1</sup>decade<sup>-1</sup>).

554 Perhaps the most significant outcome of the VMFC adjustment is the improved agreement  
 555 with LSM P-ET in terms of regional trend patterns and their amplitudes. With these adjustments  
 556 the pattern correlation of the trends increases from 0.41 to 0.55. Two applications of a 9-point  
 557 spatial filter were used prior to determining the correlations that raised the correlations by about  
 558 0.09. To gauge how sensitive this result is to our selection of modes we repeated the analysis with

559 1-, 2- and 3-mode only corrections. The resulting pattern correlations for the ensemble mean  
560 VMFC\* with the LSM mean were .048, 0.48 and 0.50, respectively. Higher modes ( $n > 5$ ) were  
561 examined but their relationship to satellite changes was not clear; in keeping with a conservative  
562 approach to making corrections these were not used. Individual pattern trend correlations were:  
563 JRA-55 = 0.48, ERA-I = 0.61, MERRA = 0.43, MERRA-2 = 0.44 and CFSR = 0.38. Though  
564 ERA-I exceeded the ensemble mean, the value for an ensemble with ERA-I removed is 0.52, thus  
565 supporting the value of an ensemble strategy as generally providing more skill than individual  
566 ensemble members.

567 The agreement in trend patterns and amplitudes between VMFC\* and the LSMs (Figure 7,  
568 bottom and Figure 4d) is therefore quite improved over the raw VMFC. Studies seeking to explain  
569 decadal changes and trend patterns like these have consistently pointed to SST variations as  
570 important controls on regional hydrologic anomalies even if details of patterns, seasonality, and  
571 intensity remain unresolved. The AMO has been found to influence rainfall over the Sahel  
572 (Folland et al, 1986; Giannini et al, 2003), northeast Brazil (Hastenrath and Greisher, 1990;  
573 Folland et al, 2001) and the U.S. (Enfield et al, 2001). Gloor et al. (2013) note the effects of  
574 Atlantic SST changes on the upward trend in wet season rainfall over Amazonia since 1980. Low  
575 frequency ENSO-like behavior of Pacific SSTs (Power et al, 1999; Zhang et al, 1999) has been  
576 argued as forcing for Global Monsoon variations (Wang et al, 2012). Positive phases of the PDO,  
577 the North Pacific component of this SST variability, are associated with an increase in  
578 precipitation in the central and northern parts of the Amazon but decrease in the southern parts  
579 (Marengo, 2004). These PDV teleconnections are global as evidenced by Lyon and DeWitt (2012)  
580 who have shown that recent Spring declines in East African rainfall are tied to cold eastern tropical  
581 Pacific SSTs. Asefi-Najafabady and Saatchi (2016) have noted a continued downward trend in

582 precipitation over central Africa by merging CRU and TRMM data, though Washington et al.  
583 (2013) strongly caution against reliance on any precipitation data set in this part of Africa.

584

585 *b. Adjustment effects on interannual variability*

586 Time series of globally-averaged VMFC for the individual corrected reanalyses are given in  
587 Figure 8a with Figure 8b showing time series area-averages of ensemble corrected reanalyses and  
588 the mean LSMs. Comparing Figure 8a to Figure 1a the reduced trends reveal more consistent  
589 interannual VMFC signals among the reanalyses and the relationship between interannual VMFC\*  
590 and Niño 3.4 SST anomalies is much clearer. Ensemble mean reanalyses and LSMs (Figure 8b)  
591 correlate well ( $\text{cor} = 0.86$ ). Ensemble averaging over multiple AMIP experiments reduces internal  
592 atmospheric variations (i.e. “weather noise”) that cannot represent the correct deterministic signals  
593 that were observed (Battisti and Bretherton, 2000). Thus, the remaining AMIP signal is only that  
594 component forced by SST. Differences in AMIP P-ET or VMFC anomaly response structure to  
595 SST anomalies are also present. These factors lower the AMIP correlation with the LSMs and  
596 VMFC\* ( $\text{cor} = 0.64$  and  $\text{cor} = 0.52$ , respectively). The agreement between the three data sets thus  
597 confirms the significant role that interannual SST variations play in land / ocean moisture  
598 exchange.

599 To explore the degree to which spatial VMFC patterns have been affected, we assess the  
600 changes in VMFC (equivalently, P-ET) patterns via ACC, this time between the individual  
601 corrected reanalyses and the ensemble LSM (Figure 9). The ACC of the ensemble mean raw  
602 reanalyses is also plotted (black dotted line) which indicates that on average the adjustment  
603 process has slightly degraded VMFC agreement with P-ET (less than 0.05 on average). Here we  
604 see that on an individual reanalysis basis, the ACC is typically only 0.35 to 0.60. Again, some of

605 this limitation is local to regional details of the ensemble LSM P-ET values. But the skill of the  
606 ensemble mean corrected reanalysis exceeds that of the individual members.

607 An indication of where VMFC and P-ET agreement has changed can be gleaned from local  
608 correlations between their time series (Figure 10). There is excellent agreement in locations of  
609 dense station sampling and significant rainfall but there is a strong resemblance between Figure  
610 10a and the S/N estimates of Figure 6b. This indicates the significant limitations of the LSM  
611 signals likely produced by rain gauge sparse density. This lack of station coverage means that in  
612 some areas even where the corrected reanalyses are improved the LSMs have such poor ability to  
613 discern signals that they cannot confirm this. Changes in correlation with the LSM ensemble P-ET  
614 compared to the raw reanalyses is shown in Figure 10b. There are areas of improvement as well as  
615 reduced agreement. Many areas in the tropics are improved, but the sparsely gauged areas in  
616 Africa and the headwaters of the Amazon are not. In central Asia agreement with the LSMs shows  
617 both strong positive and negative changes in VMFC / LSM agreement.

618 The results of Figures 9 and 10 might raise concerns about the effect the REOF adjustments  
619 have on interannual signals. To check this we composited VMFC and P-ET anomalies based on  
620 warm Nino 3.4 SST anomaly maxima during boreal winters 1982/1983, 1986/1987, 1991/1992,  
621 1994/1995, 1997/1998, 2004/2005 and 2009/2010 (not shown). Pattern correlations of VMFC  
622 and VMFC\* with P-ET were 0.82 and 0.79, respectively. All three composites had regional  
623 anomaly patterns the canonical precipitation anomalies first isolated by Ropelewski and Halpert  
624 (1987) and more recently by Camberlin et al. (2001), Grimm (2003), Hendon (2003) and Malhi  
625 and Wright (2004). We conclude from these results that interannual variability related to SST  
626 forcing is not significantly altered by our RPCA adjustments.

627

## 628 8. Conclusions

629 In this study we have sought to characterize the uncertainties in estimating variations in  
630 moisture transport of moisture from ocean to land. Reanalyses and LSMs offer two nearly  
631 independent methodologies for estimating components of the atmospheric water budget. On  
632 seasonal and longer time scales moisture transport should be equivalent to net precipitation minus  
633 evaporation. Though reanalyses offer VMFC estimates determined from dynamical modeling  
634 constraints on observations, the episodic introduction of new data sources, particularly satellite  
635 data streams, has introduced serious time dependent biases. LSMs offer similar physically-based  
636 constraints on precipitation and surface meteorological forcing in determining P-ET. Though these  
637 forcings also have their own uncertainties our assessment shows that they offer a strong  
638 quantitative assessment of VMFC issues. We have also shown that RPCA diagnostics, though ad  
639 hoc, can be applied to adjust the raw VMFC estimates. A posteriori, these error reductions are  
640 justified by improved agreement of regional trends between the LSM P-ET and VMFC regional  
641 trends. Our findings can be summarized as follows:

642 i. The large trends in near-global mean moisture convergence over land during the period  
643 1979-present in reanalyses are predominantly an artifact due to changes in assimilated data  
644 streams and the ability of those data streams to correct model biases. These biases differ  
645 among reanalyses due to their differing physical parameterization formulations and aspects of  
646 the data assimilation methodology. Averaged over the ensemble LSMs a small net positive  
647 trend in P-ET ( $0.007 \text{ mmd}^{-1}\text{decade}^{-1}$ ) is found, but is only significant at 90% confidence.

648

649 ii. Corrections to VMFC (P-ET) using RPCA with pre-filtering to identify the non-physical  
650 signal are effective in removing many of the problems and substantially enhance the agreement



in regional P-ET trends during the 1979-2012 period. RPCA-based adjustments also result in an improvement in trend field correlation from  $\text{cor}=0.41$  to 0.55. Simple PCA is likely to fail as signals of the artifacts and those of physical variability are mixed. The decision on how many modes are needed to represent artifact structure in any reanalysis is subjective and depends on cross-referencing RPCA results with assimilated observational data stream metadata.

iii. Interannual ENSO-related variations and their decadal-scale modulation are highly consistent between the LSMs and adjusted VMFC time series ( $\text{cor} = 0.86$ ) and composite El Niño P-ET and VMFC patterns ( $\text{cor} = 0.84$ ). Though the adjustments are not needed to detect these interannual signals (Figure 1a), the agreement between VMFC\* and P-ET interannual variability is more evident in time series plots (Figure 8b).

iv. Despite uncertainties inherent with observationally-constrained LSMs, these syntheses can help identify and corroborate more problems associated with reanalysis data changes. The sparseness and uneven sampling of precipitation gauging in remote areas (e.g. tropical continents, especially central Africa) are a significant uncertainty in estimating interannual variability. However, corrections to near-surface meteorology and radiative forcing are important (Ngo-Duc et al, 2005) and need additional scrutiny.

v. CMIP5 AMIP experiments, despite having somewhat distorted VMFC patterns not directly studied here, also corroborate our estimated VMFC\* corrections. Though not encumbered with the effects of changing observing systems, these experiments can only confirm the role of SST

forcing since internal atmospheric variability is only at best stochastically consistent with the historical record.

How do we envision the utility of the present results? The broader problem of reconstructing water and energy budget variability, whether from reanalyses assimilating observations or from diagnostic methods (e.g. Pan et al, 2012; Van Dijk et al, 2014; Rodell et al, 2015; L'Ecuyer et al, 2015) requires identifying and accounting for time dependent biases. The present results are a step in that direction in that they would facilitate combining VMFC and P-ET estimates in a diagnostic approach. From a broader perspective additional opportunities are apparent for indirect checks and estimates of VMFC in (1) and (2). Satellite retrievals of  $W_a$ , P and ET are one direct means. The accuracy of these retrievals varies according to space and time. Robertson et al. (2014) have recently shown that existing P and especially E estimates over global oceans have serious uncertainties for the purpose of climate variability studies. Though retrieval physics errors contribute to these problems the inter-calibration of multiple sensors and temporal changes in global sampling are also important issues. Improvements are actively being pursued. The lack of robust passive microwave remote sensing before late 1987 on which these retrievals are based is a limitation. From the terrestrial side, eq. (2), it is possible to determine changes in  $W_T$  directly via the Gravity Recovery And Climate Experiment (GRACE) satellite mission (Tapley et al., 2004), and with RO measurements from river and streamflow gauges, recover a P-ET estimate. Though GRACE measurements are a unique resource for enabling this approach those data exist only since 2003.

Another source of information may come from reduced observation reanalyses that in addition to SST, sea-ice and radiative constituents, also assimilate surface pressure observations (Compo et

696 al, 2011) and marine wind speeds (Poli et al, 2015). While these less robust data constraints also  
697 perhaps minimally enforce actual synoptic weather realism, discontinuities in their multi-decadal  
698 records appear to be less of a problem than those in the satellite record. These limitations are offset  
699 by the property that the SST (and surface pressure) forcing is largely free from the more discrete  
700 changes in atmospheric observing systems. Conceivably these integrations could also be run with  
701 observed land surface forcing as was applied in MERRA-2.

702 Ideally, improved model physical parameterizations and removal of data stream biases would  
703 mean that analysis increments or innovations would essentially be unbiased and normally  
704 distributed. However, model physics improvements (e.g. AGCM convective, turbulence and cloud  
705 parameterizations; LSM soil, vegetation and water routing formulations) are long-term  
706 development efforts and our discontinuous data streams, particularly from satellites, will always  
707 present a time varying capability to correct assimilating model errors in water and energy fluxes.  
708 Continued re-evaluation of these modeling, retrieval and in situ resources is necessary to narrow  
709 uncertainties in quantifying climate variability.

710

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 1015 *Resour. Res.*, **46**, W06507, doi:10.1029/2009WR007811.  
 1016 Zhang, Y., J. M. Wallace, and D. S. Battisti, 1997: ENSO-like inter-decadal variability: 1900–93.  
 1017 *J. Climate*, **10**, 1004–1020.

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1019 Table 1. Trend statistics ( $\text{mmd}^{-1}\text{decade}^{-1}$ ) for VMFC\* over land for various reanalyses and P-ET  
1020 for LSM members over the period 1979 to 2012. In parentheses are errors calculated using lag-one  
1021 statistics to account for serial autocorrelation.

Land Surface Model	MERRA-Land	MERRA-2	ERA-I Land	GLDAS NOAH	ORCHIDEE	CLM4C	MPI- BGC
P-ET Trend	0.023 (+/-0.019)	-0.002 (+/- 0.019)	-0.001 (+/- 0.017)	0.022 (+/-0.012)	0.009 (+/- 0.017)	0.023 (+/-0.015)	0.028 (+/-0.022)
Reanalysis	MERRA	MERRA-2	ERA-I	JRA-55	CFSR		
VMFC* Trend	0.073 (+/- 0.026)	0.003 (+/- 0.026)	0.081 (+/- 0.020)	-0.030 (+/- 0.018)	0.074 (+/- 0.025)		

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1024 Table 2. Summary characteristics of reanalysis data sets used in this study.  
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	Attributes	References	Comments
<b>ERA-I</b>	Cy31r2, 2006 IFS 80 km (T255 spectral) grid with 60 vertical levels, Jan1979-Dec2012.	Dee et al. 2011; Dee and Uppala 2008; 2009; Simmons et al, 2010	4-DVar system with adaptive estimation of satellite bias correction. RTTOV radiation operator, many revised analysis and physics improvements over ERA-40 (e.g. humidity, O3). <a href="http://apps.ecmwf.int/datasets/">http://apps.ecmwf.int/datasets/</a>
<b>JRA55</b>	JMA Dec2009 Operational System. TL319L60 (~55km). Jan1958- Dec2012.	Kobayashi et al, 2015; Ebata et al, 2011	Many updates over JRA25 including a new radiation scheme, 4D-Var, Variational Bias Correction for satellite radiances, varying greenhouse gases. <a href="http://jra.kishou.go.jp/comm/application_en.html">http://jra.kishou.go.jp/comm/application_en.html</a>
<b>MERRA</b>	GEOS-5.2.0 AGCM 0.5° x 0.667° grid; 72 vertical levels. Jan1979-Dec2010.	Rienecker et al.2011; Trenberth et al, 2011; Bosilovich et al, 2011; Robertson et al, 2011.	3D-Var Gridpoint Statistical Interpolation Scheme (GSI) with incremental Analysis Update (IAU). <a href="http://disc.sci.gsfc.nasa.gov/uui/search/%22MERRA-2%22">http://disc.sci.gsfc.nasa.gov/uui/search/%22MERRA-2%22</a>
<b>MERRA-2</b>	GEOS-5.12.4 AGCM 0.5° x 0.667° grid ; 72 vertical levels. Jan1980-Dec2012.	Molod et al, 2015; Takacs et al, 2015; Kleist et al. 2009b	GSI, IAU; Significant additional new satellite data assimilated; Now conserves dry air mass. <a href="http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl?LOOKUPID_List=MAIMCPASM">http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl?LOOKUPID_List=MAIMCPASM</a>
<b>CFSR</b>	GFS 2009 T382L64 coupled atmosphere-ocean-land surface-sea ice system, Jan1979-Dec2009.	Saha et al. 2010; Wang et al, 2010; Trenberth and Fasullo, 2013	3DVar GSI system, AER Radiation, Noah LSM with MOM ocean model Ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. <a href="http://www.cgd.ucar.edu/cas/catalog/reanalysis/index.html">http://www.cgd.ucar.edu/cas/catalog/reanalysis/index.html</a>

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Table 3. Observationally constrained Land Surface Models providing P and ET in this study.

Model	Attributes	Forcing	Comments and references
<b>CLM4C</b>	Five primary sub-grid land cover types (glacier, lake, wetland, urban, vegetated) in each grid cell. The vegetated portion of a grid cell is divided into patches of plant functional types with separate energy and water calculations.	Based on a merged product of Climate Research Unit (CRU) observed monthly 0.5 analysis (v3.0, 1901–2009; New et al, 2000) and the high temporal fidelity NCEP reanalysis forcing.	Land model for the National Center for Atmospheric Research (NCAR) Community Earth System Model and the Community Atmosphere Model. (Oleson et al, 2010; Lawrence et al, 2011; Weedon et al, 2011). <a href="http://www.cesm.ucar.edu/models/clm/">http://www.cesm.ucar.edu/models/clm/</a>
<b>ERA-I Land</b>	Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL). 80 km res with 3h integration steps.	ERA-Interim near surface meteorology and radiation. ERA-I precipitation is rescaled using GPCP v2.1.	Updated physics including soil hydrology, a new snow scheme, multi-year satellite based vegetation climatology. (Balsamo et al, 2012, 2015). <a href="http://www.ecmwf.int/en/research/climate-reanalysis/era-interim/land">http://www.ecmwf.int/en/research/climate-reanalysis/era-interim/land</a>
<b>GLDAS-2 Noah</b>	1-D column model which can be executed in either coupled or uncoupled mode. Governing equations of the physical processes of the soil-vegetation-snowpack medium.	Updated Sheffield et al. (2006) forcing dataset based on the NCEP–NCAR reanalysis near-surface meteorological variables. GPCP, TRMM precip, SRB Radiation. CRU meteorological data used to correct biases.	Development began 1993 through a collaboration of investigators from public and private institutions, spearheaded by the National Centers for Environmental Prediction. (Chen et al, 1996; Koren et al, 1999; Rodell, 2004.) <a href="http://ldas.gsfc.nasa.gov/gldas/">http://ldas.gsfc.nasa.gov/gldas/</a>
<b>MERRA-Land</b>	GEOS-5 Six-layer catchment land surface model Koster et al. 2000. The basic land surface element, or “tile,” is a topographically determined hydrological catchment non-congruent with overlying MERRA lat x lon grid	Precipitation forcing with the global gauge-based NOAA Climate Prediction Center “Unified” (CPCU) product.	Generated by offline version of the land component of the MERRA system. Revised parameter values in the rainfall interception model from those in the MERRA surface meteorological forcings. (Reichle et al, 2011; 2012). <a href="http://gmao.gsfc.nasa.gov/research/merra/merra-land.php">http://gmao.gsfc.nasa.gov/research/merra/merra-land.php</a>
<b>MERRA-2</b>	Updated version of catchment model used in MERRA.	Precipitation constraints comprised of anomalies from CMAP V0011 and RT pentad product plus GPCP v2.1 climatology. Near surface meteorology and radiation from MERRA-2.	MERRA 0.5 deg, hourly time series of precipitation (background) are constrained to have the same daily totals as constraining CMAP/GPCP data. (Reichle and Liu, 2014). <a href="http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2">http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2</a>
<b>MPI-BGC</b>	Machine-learning methodology, “model tree ensembles”, to up-scale eddy covariance (EC) measurements from FLUXNET (Baldocchi et al. 2001) to a 0.5 degree monthly product	AVHRR NDVI data SeaWiFS fPAR; CRU near-sfc temperature	ET estimates use GPCC V6 precip in classification step (Jung et al., 2009; 2010.). We thus use GPCC precip to make consistent P- ET. <a href="https://www.bgc-jena.mpg.de/bgi/index.php/">https://www.bgc-jena.mpg.de/bgi/index.php/</a>
<b>ORCHIDEE</b>	Solves water-energy-carbon budget. Represents ecosystem in terms of a range of Plant Functional Types using big leaf approach. Computes its own phenology.	ERA-I fields constrained with CRU 3.2 Sfc air temp and GPCC v6 monthly precip  Forcing precipitation, air temperature, wind, solar radiation, humidity and atmospheric CO <sub>2</sub>	SECHIBA land-surface scheme, which is dedicated to the surface energy and water balances, and the carbon and vegetation model STOMATE. Krinner et al, 2005; Weedon et al. (2012); Sitch et al, 2013; Poulter (personal communication). <a href="http://forge.ipsl.jussieu.fr/orchidee/wiki">http://forge.ipsl.jussieu.fr/orchidee/wiki</a>

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## Figure Captions

Figure 1. (a) Time series of global land area-average ( $60^{\circ}\text{N/S}$ ) vertically-integrated moisture convergence anomalies (VMFC) from various reanalyses. Units are  $\text{mmd}^{-1}$  (left hand side scale). Niño 3.4 SST anomalies ( $^{\circ}\text{C}$ ) are shaded gray with inverted scale on the right hand side. (b) Same as above but for P-ET from individual LSMs. Ensemble mean is shown in black. Units are  $\text{mmd}^{-1}$ . For both time series a three month running smoother has been applied for display purposes.

Figure 2. Annual mean anomalies of LSM ensemble mean P-ET and globally-integrated streamflow from Dai (2016). Units are  $\text{mm yr}^{-1}$ . LSM monthly anomalies from Figure 1 have been summed over water year intervals beginning in October 1979.

Figure 3. Statistics for monthly mean VMFC anomalies for various reanalyses over the period 1979-2012. *Left (a-e):* RMS of deviations ( $\text{mmd}^{-1}$ ). *Right (f-j):* Trends ( $\text{mmd}^{-1}\text{decade}^{-1}$ ).

Figure 4. Ensemble mean statistics for reanalysis and LSM monthly anomalies over the period 1979-2012. *Left panel:* RMS ( $\text{mmd}^{-1}$ ). *Right Panel:* Trends ( $\text{mmd}^{-1}\text{decade}^{-1}$ ).

Figure 5. Time series of reanalyses VMFC and ensemble LSM anomalies ( $\text{mm d}^{-1}$ ) over (a) Equatorial Africa (c) Coastal Colombia / Ecuador region, and (d) Central U.S. (c) Shows MERRA VMFC (red) and first two global PCs of vertically-integrated moisture increment.

Figure 6. (a) Ensemble mean climatological P-ET ( $\text{mmd}^{-1}$ ). (b) S / N for LSMs (see text for details on calculation). (c) P-ET ACC time series of each LSM with the ensemble mean.

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1058 Figure 7. (*Left*) Time series of globally averaged, 60° N/S, reanalysis VMFC (black) and area-  
1059 averaged corrections (red). Niño 3.4 SST x 0.1 is plotted as gray shading with inverted scale on  
1060 right hand side. (*Right*) Trends ( $\text{mmd}^{-1} \text{ decade}^{-1}$ ) in VMFC\* over the period 1979-2012 for  
1061 various reanalyses after corrections have been applied. Compare to Figure 3, *right* which are the  
1062 uncorrected trends. (Bottom) Ensemble mean corrected VMFC\* trends.

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1064 Figure 8. (*a*) Time series of individual corrected reanalysis VMFC\* global land area-average  
1065 (60°N/S). (*b*) P-ET from individual LSMs (black) and mean VMFC\* from corrected reanalyses  
1066 (red) and AMIPs (cyan). A three-month running smoothing is applied. Units are  $\text{mmd}^{-1}$ . Niño  
1067 3.4 SST anomalies are plotted in gray shading with inverted scale (deg C) on right.

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1069 Figure 9. Anomaly correlations, ACC, between individual corrected reanalysis VMFC\* and  
1070 ensemble mean LSM P-ET. ACC for the ensemble corrected and uncorrected reanalyses with the  
1071 ensemble LSMs is shown by the solid (dotted) black lines, respectively. A running 3-month  
1072 smoother has been applied to each time series for display.

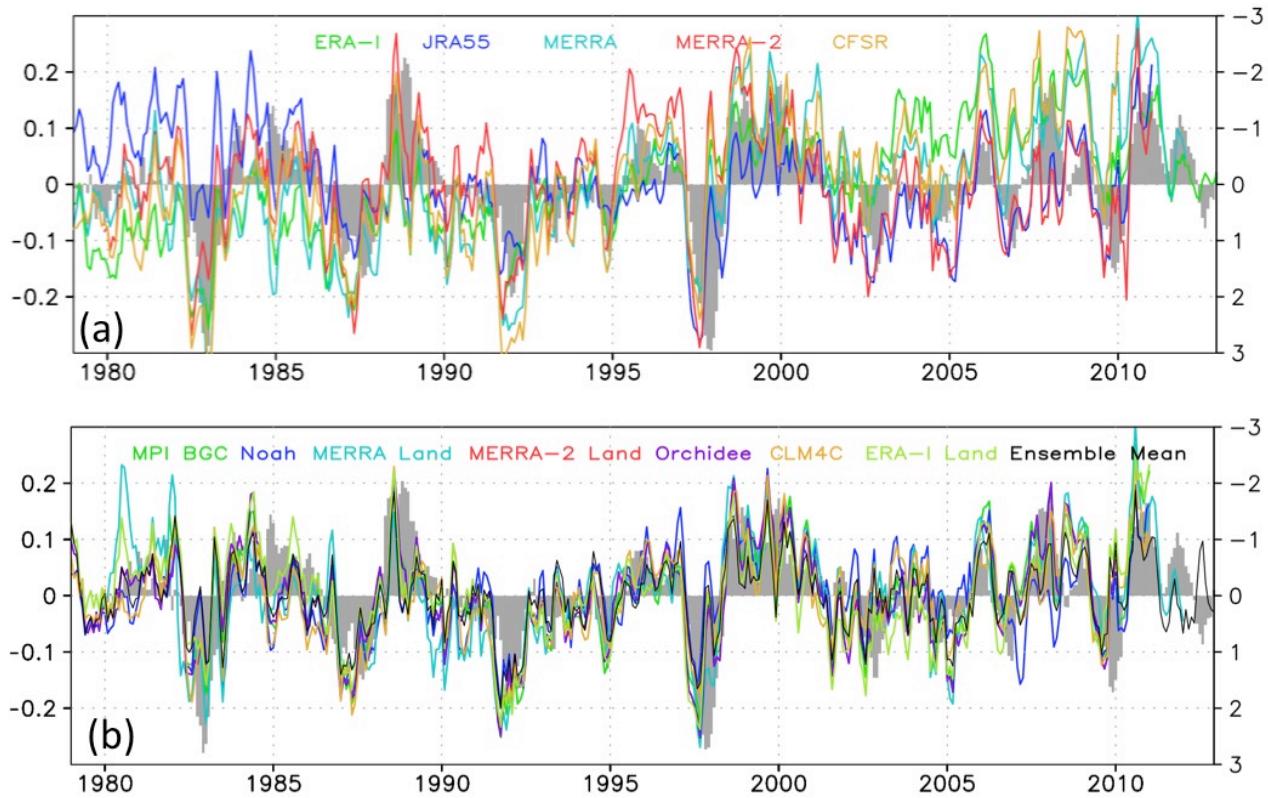
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1074 Figure 10. Local correlations (1979-2012): (*a*) Ensemble mean adjusted reanalysis VMFC\* and  
1075 ensemble mean LSM P-ET, (*b*) Adjusted VMFC\* correlation with LSMs minus raw reanalysis  
1076 ensemble reanalyses VMFC correlation with ensemble LSM P-ET. Note different color scales.

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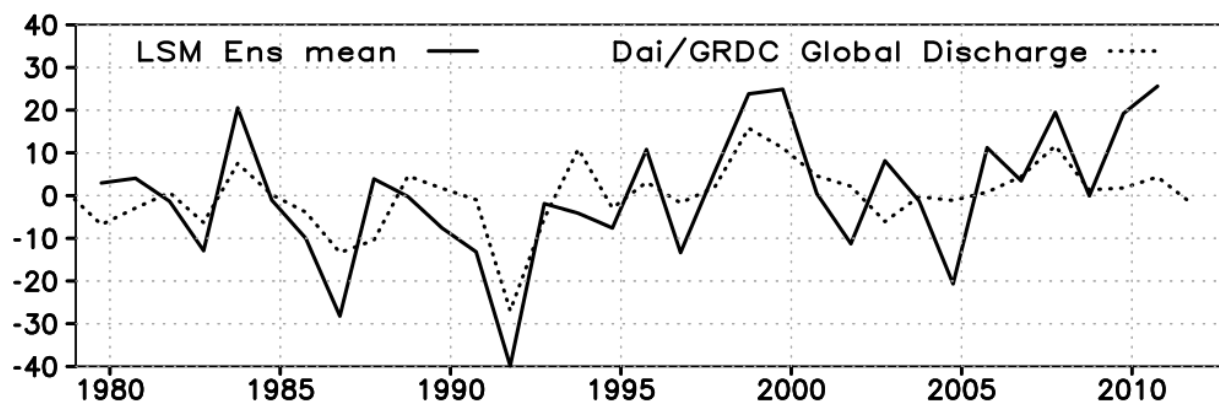
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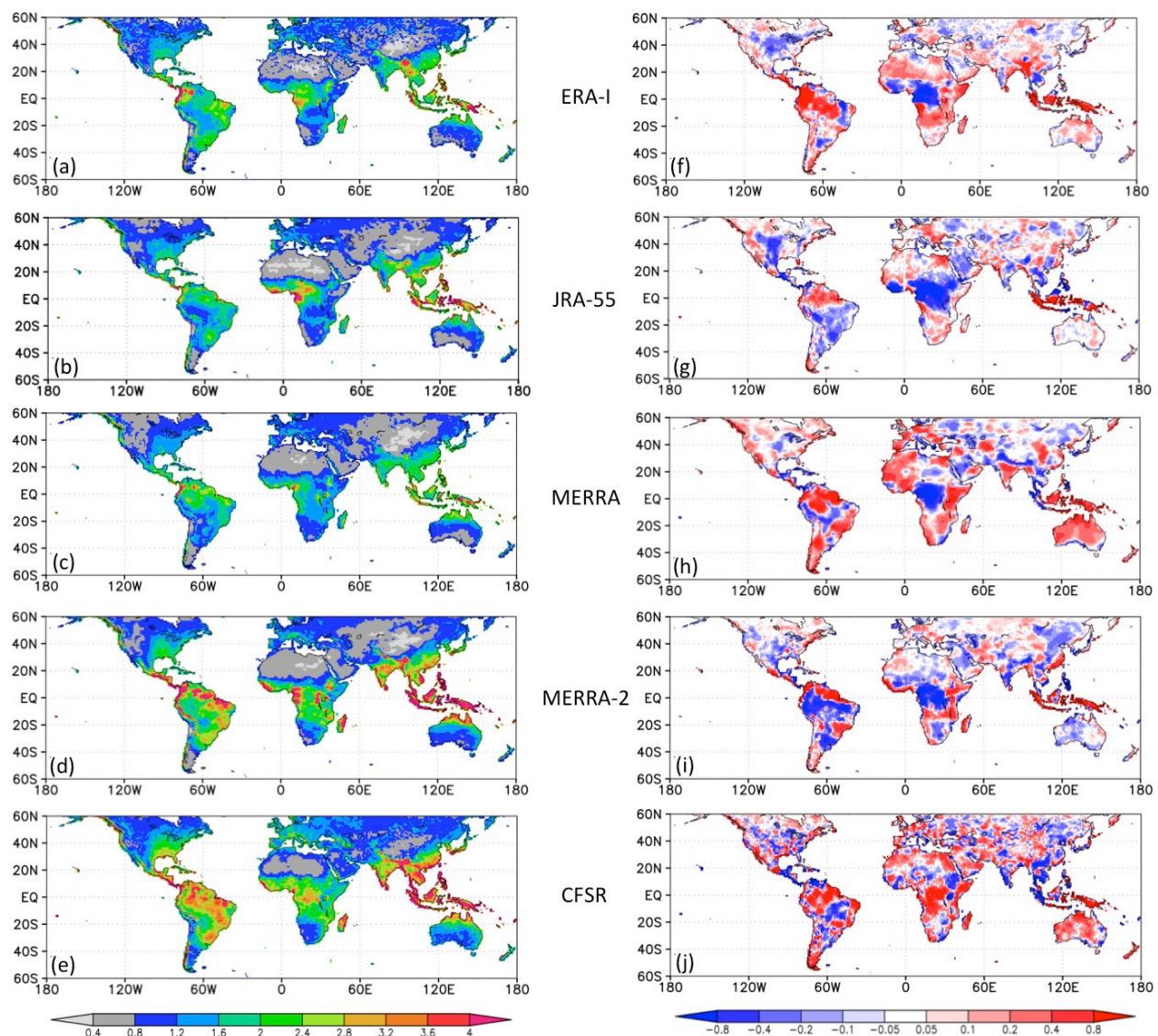
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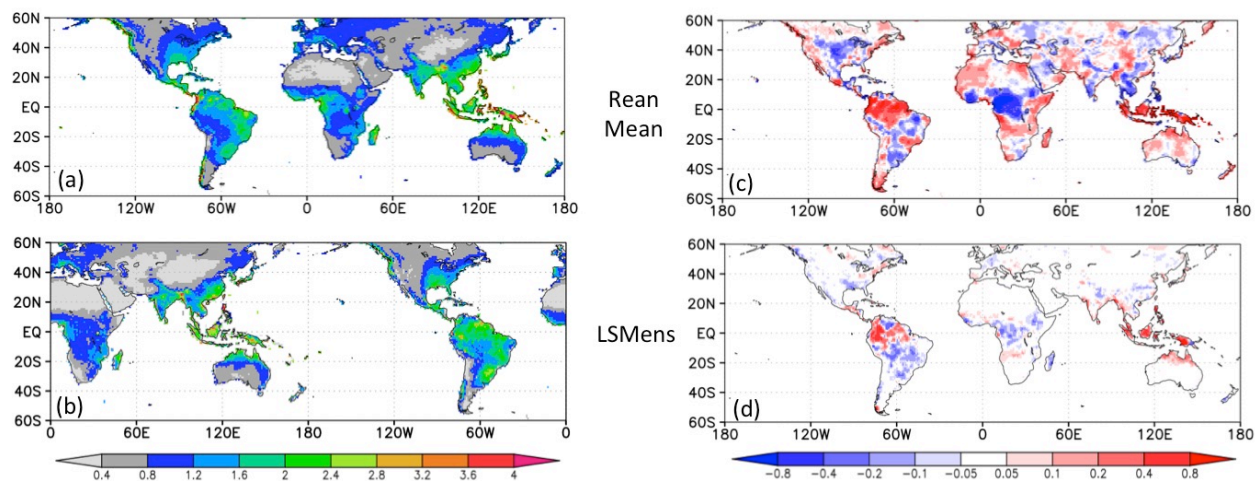
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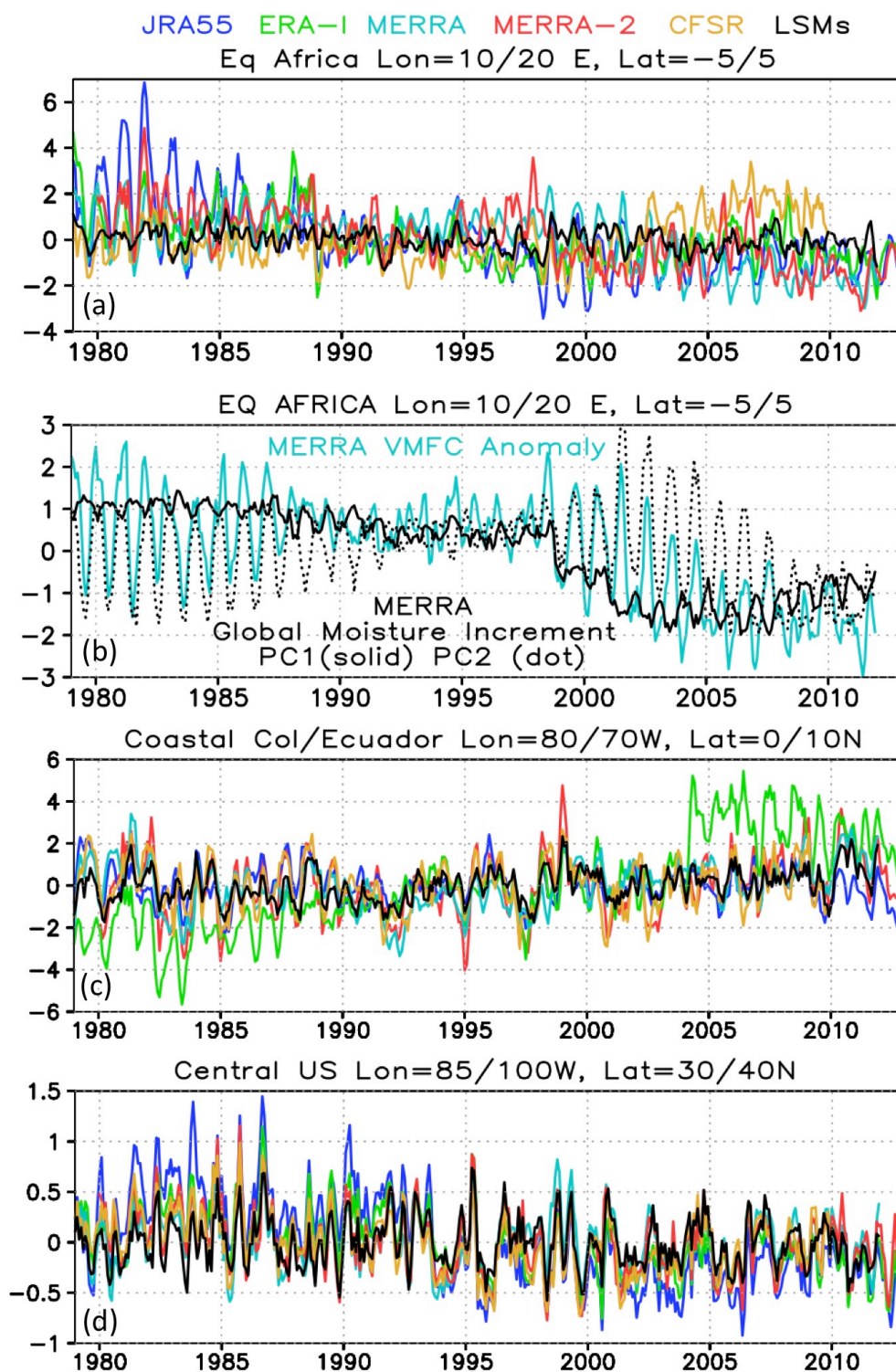
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Figure 4. Ensemble mean statistics for reanalysis and LSM monthly anomalies over the period 1979-2012. *Left panel:* RMS (mm d<sup>-1</sup>) . *Right Panel:* Trends (mm d<sup>-1</sup> decade<sup>-1</sup>).

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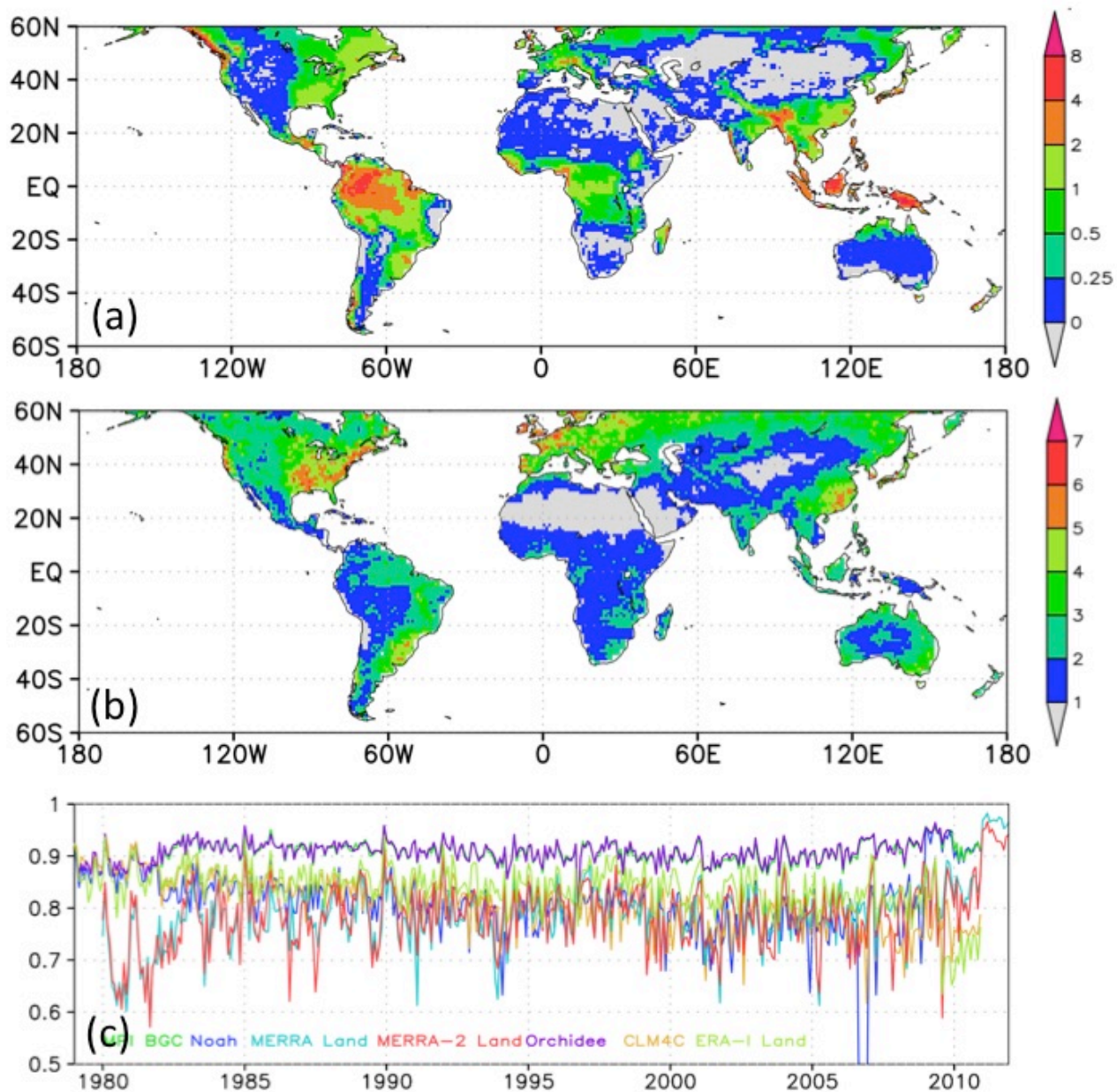
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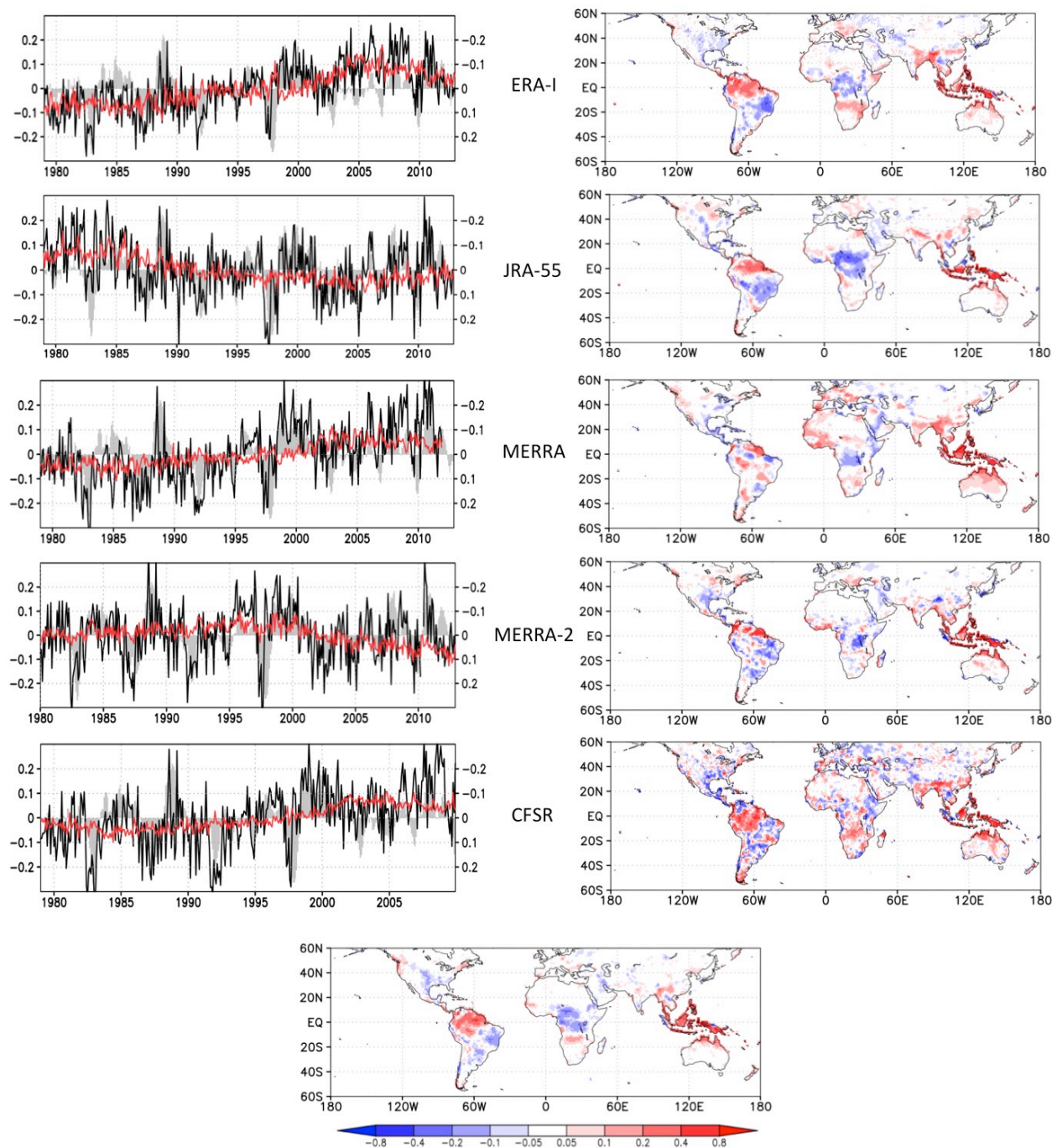
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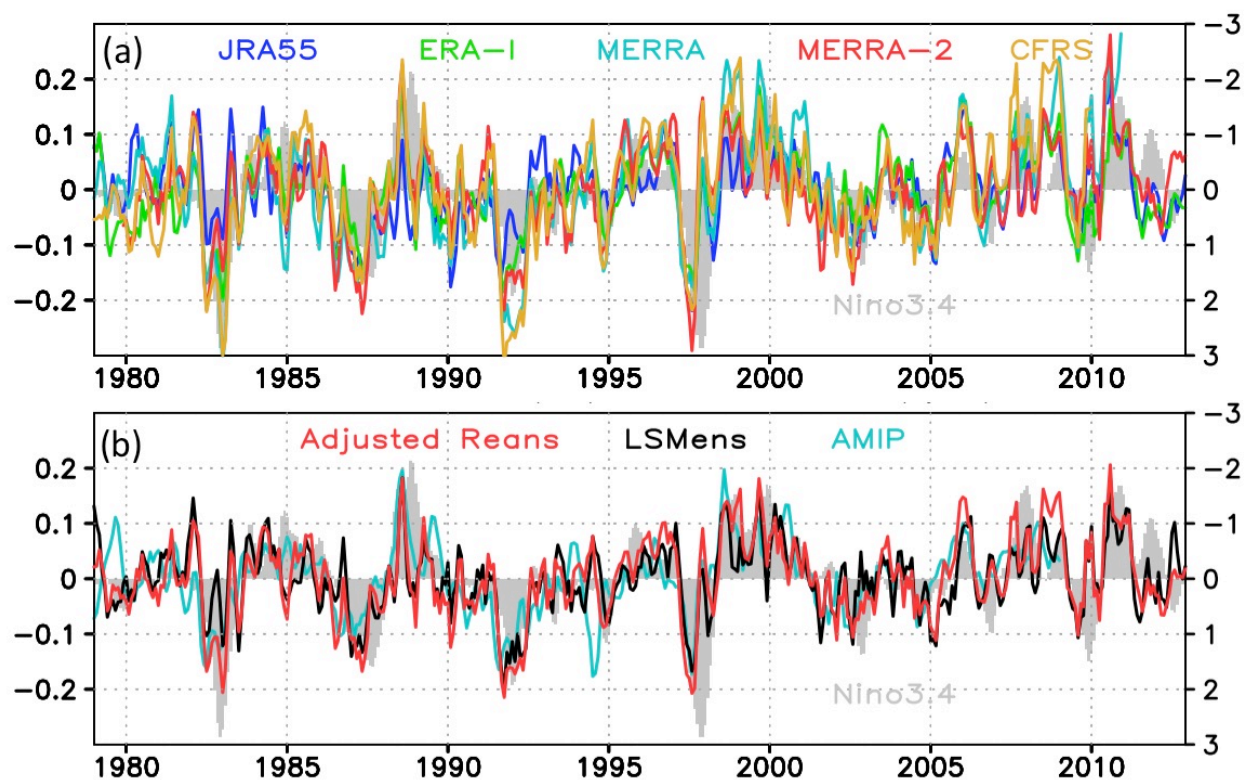
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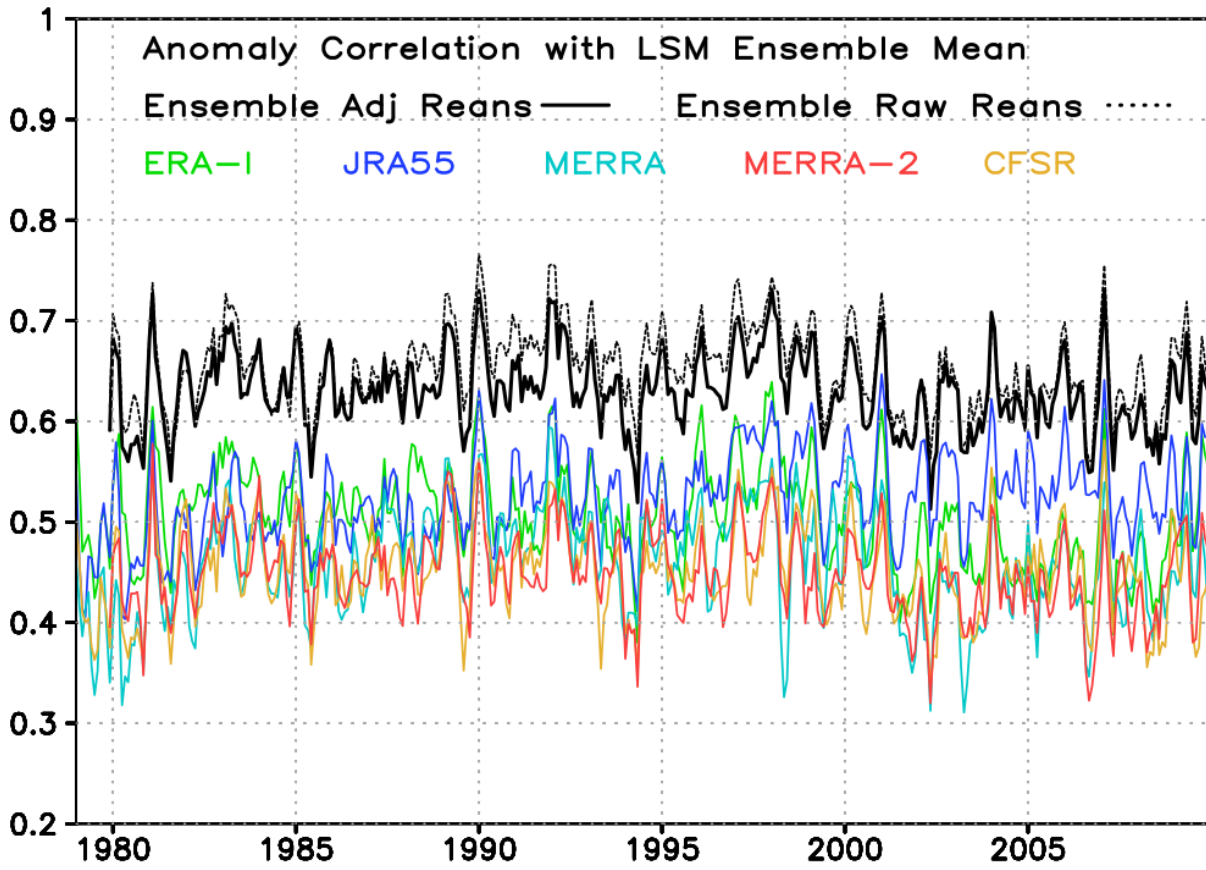
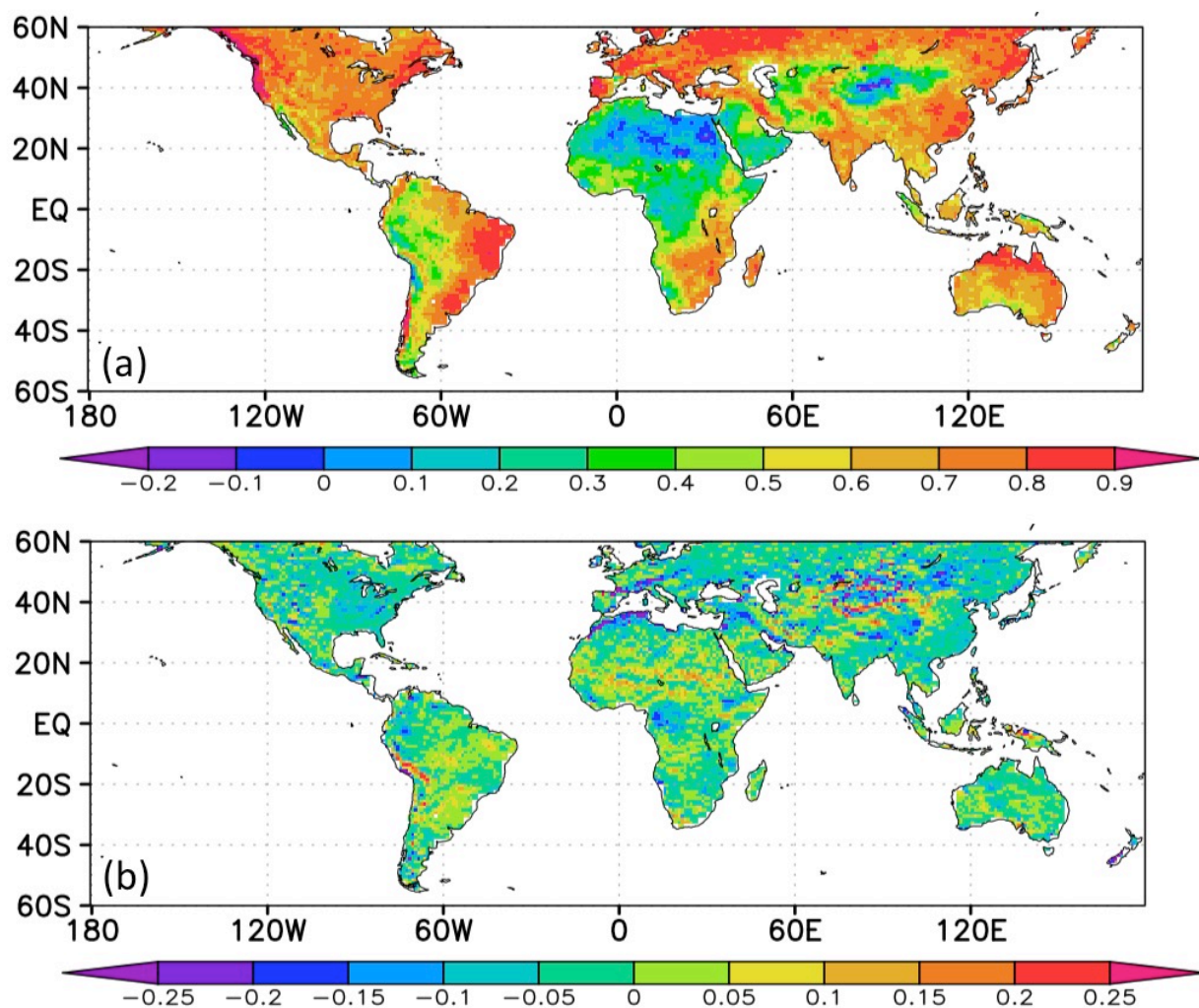


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